Precision calculations for future e+e- colliders: targets and tools

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Welcome to the workshop

- The goal of the workshop is to identify clear theoretical and computational tools for high-precision predictions of relevance to the programme of future e+e- colliders
- Week 1 (last week): focused on the key physics questions and observables that demand a theory input
- Week 2 (this week): focuses on modern advancements in multi-loop calculations and future applications to match the precision goals
- Beyond the workshop: the programme is not comprehensive, and does not cover other important topics such as Monte Carlo generators and jet physics. These are left for future dedicated events

Welcome to the workshop

- One outcome of the 2 week workshop is to summarize the precision goals in one document, may be posted on arXiv for future reference
- This week we look for more technical talks which address precision goals set in the first week
- We hope that the participants use the opportunity to interact and work on possible future collaborations tackling the precision goals

Logistics

- The programme consists of 3-4 talks a day: 40' + 20' for discussions
- The mornings are left free and can be used for spontaneous discussions and collaboration work
- Coffee is served every day at 10am and 3pm (2pm on Friday) in the TH common room (4/2-011)
- A small reception will be served today at 5pm in front of the main auditorium
- For any questions or requests, please contact us at fcee-wshop-pc@cern.ch

Short summary of week 1

In my view the first week of the workshop is a success

- We had 12 talks each 40' with 20' discussion afterwards
- Big interest, judging by the rich participation list
- Very good quality and comprehensive talks on precision physics
- People used the in person participation for ongoing collaborations and forged new collaborations
- The people who presented their dedicated talks to precision physics are: **Patrick Janot, Ayres Freitas, Stefan Kluth, Stefano Frixione, Martin Beneke, Frank Simon, Jenny List, Li Lin Yang, Paolo Nason, Andrea Banfi, Graham Wilson, Paolo Azzurri**

My general picture of precision physics at future e+e- colliders

- The future lepton colliders will reach high precision on various SM parameters
- The ultimate target for precision is the small statistical error foreseen for the measurements
- The theorists have to catch up, most systematic errors from measurements are dominated by the theory
- Most measurements need theory input

Electro weak precision observables

- EWPO measurements at the Z-pole have a considerable physics potential, e.g.: combined with W, top and Higgs measurements they probe the fine structure of the SM and constrain heavily BSM models
- We deal with large effects in initial state QED radiation (ISR) for example to determine the line shape of the Z boson measurement
- A precise control over ISR corrections is instrumental in all measurements. Ultimately this will require improving substantially on existing MC tools
- We have to go beyond purely analytic tools, and count more on, and improve, MC event generators

Electro weak precision observables

	Experiment uncertainty			**Theory uncertainty**
	Current	**CEPC**	**FCC-ee**	**Current**
M_W[MeV]	15	0.5	0.4	4
Γ_Z[MeV]	2.3	0.025	0.025	0.4
$R_b[10^{-5}]$	66	4.3	6	10
$\sin^2\theta^{\rm l}_{\rm eff}[10^{-5}]$	16	< 1	0.5	4.5

- Theory errors in the future assume 2 loop EW corrections in $2 \to 2$, 3 loop $1 \to 2$ plus dominant 4 loop terms in EW processes and NNLO QCD corrections in heavy-quark production plus jets will become available

ISR QED for future lepton colliders

- Available tools: Pythia8, Herwig, Sherpa, MadGraph5aMC@NLO, Whizard, BabaYaga, RacoonWW, Racoon4f, KKMC-ee, KORAL[W/Z], BH[LUMI/WIDE], YSF[WW3/ZZ], ...
- YFS and collinear factorization are improvable by including fixed order corrections and resummation
- This topic will be addressed in future workshops

Possibilities and precision goals for QCD measurements

The talk and the discussion on jet observables suggests

Process	**Fixed order**	**Resummation**
e+e- $\to$ 3 jets	N3LO	N3LL and beyond
e+e- $\to$ 4 jets	NNLO	beyond NLL
e+e- $\to$ 5 jets	NNLO	beyond NLL

Non perturbative effects are a conceptual bottleneck, in general they may contribute at the $10\,\%$ level and a deeper understanding is a must

Near top-pair threshold

- Experimentalists report that theory is the dominating uncertainty for phenomenology around $\mathrm{t\bar{t}}$ threshold
- Process $\mathrm{e^+e^-} \to \mathrm{t\bar{t}}$ at NNNLO available in (PNR)QCD + top-Yukawa effects, N4LO possibly necessary to reach the target precision
- Process $\mathrm{e^+e^-} \to \mathrm{W^+W^-b\bar{b}}$ in the continuum at NNLO available with cuts and invariant mass cuts, N3LO QCD + NNLO EW possibly needed to match the precision target
- Potential to extract $\mathrm{m_t}$, Γ_t, $\mathrm{y_t}$, α_s

Higgs physics potential

- At the $\mathrm{Z\,H}$ threshold and above the target accuracy requires 2-loop EW corrections to $\mathrm{e^+e^-} \to \mathrm{Z\,H}$ and $\mathrm{e^+e^-} \to \mathrm{H}\,\nu\,\nu$, crucial for the precise determination of the Higgs width and couplings

- Kinematic distributions of hadronic Higgs decays need N3LO QCD corrections

Non-perturbative aspects of QCD at lepton colliders

- Could use the Thrust to determine the α_s
- Is sensible to non-perturbative hadronization effects, which contribute a systematic error of 10%
- Conceptual understanding of non perturbative effects requires N3LO calculations for the shape variables and NNLO+NNLL for the three jet rate and soft-drop thrust
- This topic will be addressed in future workshops

Precision EW physics above the Z-pole, W boson mass, decay rates and line shape

- Potential with ILC: a precision of 2 MeV is very likely for the determination of $\mathrm{m_W}$
- For ILC; polarization, beamstrahlung is important within every MC generator.
- Potential at the FCC: Measurement at threshold from a line shape: $\Delta\Gamma_W = 0.96$ MeV and $\Delta m_W = 0.41$ MeV
- Precise W decay BRs
- Lepton universality tests at the 10^{-4} level
- Flavor tagging of hadronic W decays; precise direct CKM measurement $|V_{cb}|$

Programme week 2

- Most tools in high energy physics are dedicated to the LHC physics
- We ask you to use your bread and butter tools and to tailor them to the requirements of the precision physics
- Thank you and enjoy the workshop